MAT JOURNALS
Journal of Remote Sensing GIS & Technology
Volume 5 Issue 1

Soil and Groundwater Remediation Proposal in an Aquifer of Venezuela by Hydrocarbon Transport Geostatistical Modeling

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DOI: http://doi.org/10.5281/zenodo.1492031

Abstract

In this paper, it is presented a remediation proposal for soil and groundwater remediation proposal in an aquifer of Venezuela by hydrocarbon transport geostatistical modeling. The contamination with hydrocarbons is occurring in the northern region of an aquifer of the Carabobo State implying that the contaminants might be transported toward downstream of the aquifer causing an impact on the water for human consumption and industrial uses. The condition of the confined aquifer due to the alternating layers of low plasticity clay with well graded sand has avoided that the hydrocarbons in the soil reach a concentration that exceeds to the environmental regulation. For groundwater, the concentration of the hydrocarbons such as TPH, TPH-GRO, Lead, Benzene, Toluene, Ethylbenzene, m.Xylene, o.Xylene and MTBE is greater than to the environmental regulation. In most of cases, the spatial prediction of hydrocarbons is explained by local polynomial interpolation of orders between 2 and 3, and in minor proportion by global polynomial interpolation of orders between 2 and 3. The gradient of the linear regression function varies between 0.34 and 0.94. The proposal of remediation for hydrocarbons in soil and groundwater consists of applying of air injection and vapor extraction, requiring an estimated air injection of 13153 m^3/d (323 cfm) and the vapor extraction of 5075 m^3/d (125 cfm). The proposed wells for air injection (42) and vapor extraction (19) in a Carabobo State aquifer separated each 100 meters and 150 meters, respectively.

Keywords: *Remediation, Groundwater, Spatial prediction model, Hydrocarbon transport*

INTRODUCTION

In this study, a remediation proposal for groundwater and soil derived from geostatistical modeling of hydrocarbon transport in an aquifer of Carabobo state, Venezuela, is presented. The aquifer is contained in an area where the main uses are urban and industrial. The source of pollution by hydrocarbons is a gas station located on one of the main highways, which connects the north-central region with the north-western region of Venezuela, which causes a great demand for fuel services by this gas station. The objective of this document is to apply spatial prediction models using deterministic methods to analyze the distribution of hydrocarbons and propose a physical and chemical remediation technology focused on achieving the removal of contaminants. The most common physical and chemical remediation technologies are pump and treat, in situ air sparging, in situ flushing and permeable reactive barriers (Darnault, 2008).

STUDY AREA

The study area is an aquifer located in the Carabobo State, which is one of the states of Venezuela belonging to the northern region in front of the Caribbean sea between the coordinates N 09°50’00”, N 10°40’00”, W67°30’00” and W68°20’00” (Figure 1). The aquifer is contained in an area bounded by the following coordinates: N 10°05’30”, N 10°11’00”, W67°59’30” and W68°03’30”. The specific zone identified as the source of hydrocarbon contamination detected by GUACAOB community council due to the existence of strong fuel odors and the presence of fuel in rainwater collection channels and denounced to the local press and the Fire Department of the Municipality of Valencia from August 2007; requesting investigation about its origin, it is a gas station known as “El Prado”, which offers services to an industrial, commercial and residential uses in the Municipality of Valencia, Carabobo State. The investigation was started by the Civil Protection and Fire Department of Valencia Municipality, and the presence of volatile gases in a high degree was confirmed. In addition, the GUACAOB (Guacamaya-Caobos) community council spokespersons asked to the PDVSA-Yagua (Petroleos de Venezuela, S.A.) company the attention to the case. From August 2008, the GUACAOB Communal Council again denounced the annoyance due to the strong odor of fuel and the presence of free product in an excavation carried out for the construction of a water well, of a neighbor of the community. In September 2008, the Ministry of Energy and Petroleum (MEP) hires to the company Racing Oil Service 2021 of Venezuela on September 12, 2008 for applying tank tightness tests with the presence of the GUACAOB Community Council, detecting continuous pressure drop to zero (0) psi in a period of 20 minutes in the # 2 gasoline tank of 91 octane, which presented a fissure (leak). The MEP suspended the sale of fuel from this cracked tank. The rest of the petrol storage tanks of 91 octane (4 tanks), 95 octane (5 tanks) and diesel (three tanks) remained operational. The MEP did continuous monitoring in a house of the Los Caobos Urban District affected by the presence of fuel in a drainage. A sample is taken and analyzed in the Yagua Plant Laboratory, which resulted in the production of 91 octane gasoline. The MEP instructed the Concessionaire for the immediate characterization of soils to determine concentrations of Volatile Hydrocarbons and the extension of the pollutant plume and correct the damages caused to third parties. In October 2008, the Concessionaire built a new water well in the affected house of Urb. Los Caobos, however, it is presumed that the soil characterization was not carried out since the supports are not presented to MEP or PDVSA. No new claims from the community are presented. Between May 2014 and September 2015, It is reiterated to the concessionaire its noncompliance with the records of inventories, auditable records and the adequate collection of the data of the gauging, mechanical and electronic readings. In January 2016, members of the GUACAOB Community Council deliver a document to the District Management Department of the Gasoline Stations belonging to the Yagua Distribution Plant, requesting the inspection of the houses located in the aforementioned residential complex as the neighbors complained of continuous strong odors to fuel, causing them discomfort and respiratory allergies especially children and older adults.

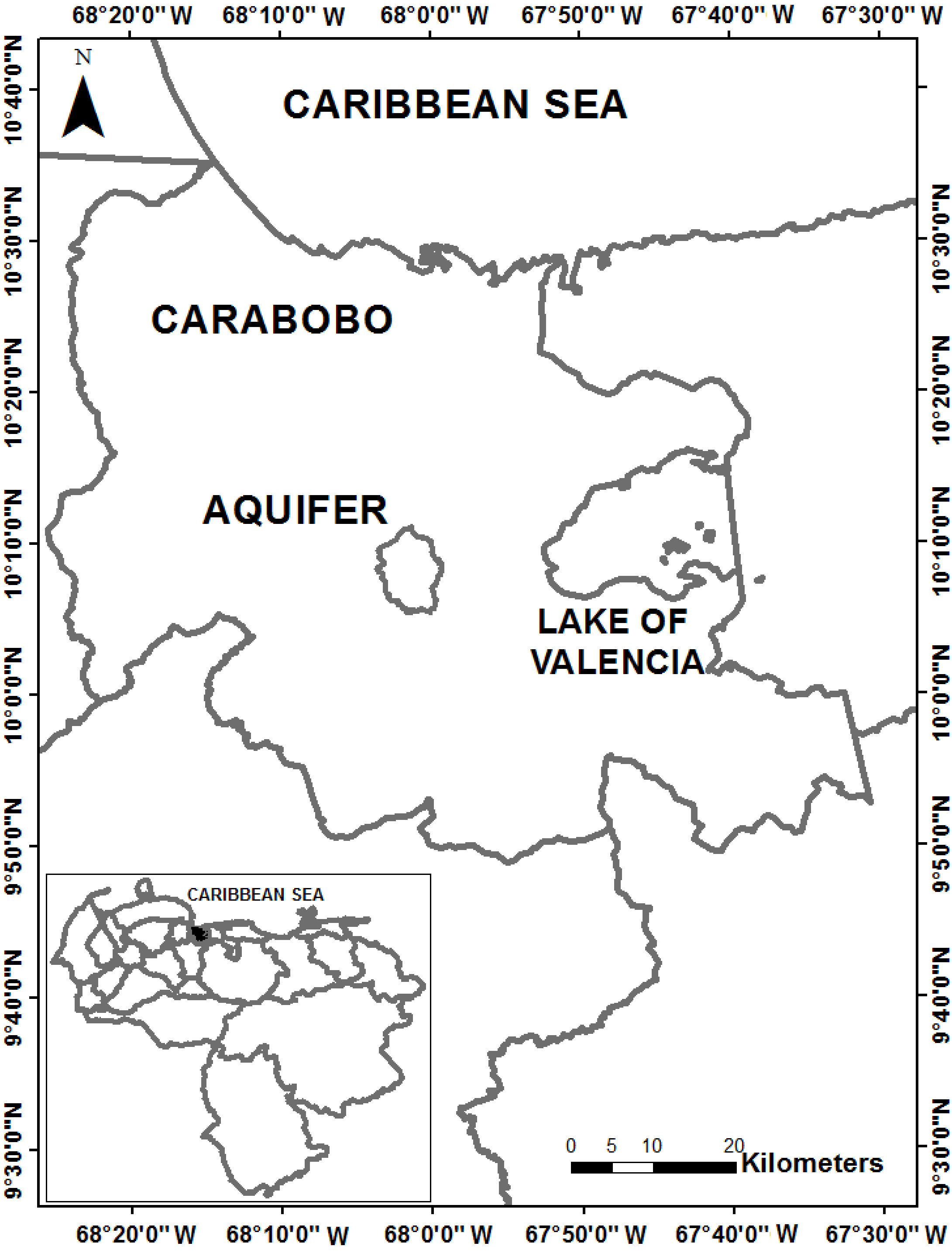


***Fig: 1.** Localization of the aquifer regarding to the Carabobo State, Venezuela*

From January 2016, inspections to the El Prado gas station to evaluate the operating conditions and analyze the inventory controls and auditable records were required by MEP and PDVSA in order to detect if there were fuel leaks that show evidence of leakage. During these inspections, it was evidenced that the Concessionaire carried out the replacement of a section of rigid petrol distribution pipe of 95 octanes without prior notification to PDVSA Company and MEP.

Between January and February 2016,

explosivity measurements were made in drainage channels of the Los Caobos community, where high values of these were found, presenting a dangerous combustible atmosphere, so a worktable was installed with all the organisms present such as PDVSA, MEP, maintenance and Sales Department, community of urbanization Los Caobos, Civil Protection and Fire Department, Ministry of Environment, Environment Department of the Mayor's Office of Valencia, to provide a solution to the problem. The actions taken were: a) Sampling of the fluid contained in the affected channel, b) tightness tests were made to pipes and volumetric tests to storage tanks for the El Prado gas station, c) Identification of other possible sources of pollution in the area (mechanical workshops, vehicle sales, production industries, d) temporary suspension of fuel sales service in the El Prado gas station as a prevention, until the tightness tests were carried out.

On February 2016, the Ministry of Environment delivers to PDVSA the results of the analysis of the samples taken in the drainage channel of rainwater, located in the Los Caobos Urbanization, Araguaney Street, in addition to the samples taken in the deep well located in Los Caobos Urbanization, Av. 113. The laboratory results indicate that the canal is being reached by a mixture of water with a high concentration of total petroleum hydrocarbons (TPH), a product that can be gasoline in concentrations that are still a risk to health and the environment.

Regarding to the conclusion of the analysis of the samples taken in the deep well: the results indicate that the well is contaminated by total petroleum hydrocarbons (TPH) with a value of 22 mg / L and presents high concentrations of total iron (Fe) and total manganese (Mn) that is above the maximum ranges or limits allowed in articles 5 and 8 of Decree 3219 for type 1 water unbundled Sub-Type 1A and 1B. Therefore, the waters are not suitable for human consumption.

Among May and August 2016, the Phase I of the environmental assessment was carried out in the Gas station El Prado with the GUEINPROCA Company. Between April and May 2017, the Geohidra Consultores Company was contracted by PDVSA Company, to develop the Project "Environmental Evaluation Phase II for the Determination of Levels of Pollution by Hydrocarbon Spilled in E / S El Prado, Carabobo State. The report presents the results obtained during the execution of the Phase II Environmental Assessment. The database used is taken from the records of the measurements, and the results of the physical and chemical analyzes of the soil and water samples.

METHODS

The database of this study has been obtained from two sources (Table 1); one is represented by Geohidra Consultores Company, which was contracted by the PDVSA Company between April and May 2017. The study can be accessed publicly from the headquarters of the Ministry of the Environment, Carabobo State. The second is a study developed by Rodriguez, (2017) to get the Science Master degree at the Environmental Engineering program of the University of Carabobo. In the first study, the activities that were developed during the phase II of the Environment Assessment implied: 1) *Construction of monitoring wells:* installation of 15 monitoring wells with a diameter of two (2) inches, distributed in the potentially affected area according to the results of the Phase I of Environmental Evaluation. As a sample, the monitoring station 1 (PM-1) is located in the coordinates: N10°09’34” and W68°01’26.9” (Table 1). The depth of the drilled wells is between 7.3 m and 22.8 m, for a total of 166.86 m of drilling. 2)

Lithological study of the subsoil, taking samples every 1.5 meters of advance in the drilling. Physical tests in the laboratory that included: texture, liquid limit, plastic limit, plasticity index, moisture content, granulometry and permeability. 3) *Collection and analysis of soil samples:* 15 soil samples were collected and analyzed, taking as a reference the concentration of Volatile Organic Compounds (VOC) in them. The following parameters were considered in the analysis: Total metals (Lead), Methyl tertiary-butyl ether (MTBE), Benzene, Toluene, Ethylenebenzene and Xylene (BTEX), Total Petroleum Hydrocarbons (TPH), TPH-GRO (GRO: Gasoline Range Organics, C_6-C_{10}), TPH-DRO (DRO: Diesel Range Organics, C_{10}-C_{12}, C_{12}-C_{16}) and TPH-ORO (ORO: Oil Range Organic, C_{16}-C_{35}). 4) *Collection and analysis of water samples:* 15 samples of groundwater were collected and analyzed, after cleaning the wells. The following parameters were considered in the analysis: Total metals (Lead), Methyl tertiary-butyl ether (MTBE), Benzene, Toluene, Ethylbenzene and Xylene (BTEX), Total Petroleum Hydrocarbons (TPH), TPH-GRO (Gasoline Range Organics, C_6-C_{10}), TPH-DRO (Diesel Range Organics, C_{10}-C_{12}, C_{12}-C_{16}), and TPH-ORO (ORO: Oil Range Organic, C_{16}-C_{35}). 5) *Measurement of the depth of the water level* in the monitoring wells constructed, and the thickness of the product or free hydrocarbon (if present).

The second study was carried out by the following activities: 1) *Description of the topographic, geological, and hydrogeological characteristics of the La Guacamaya aquifer, Valencia Municipality, Carabobo State.* Alos Palsar Satellite digital elevation model was acquired from the webpage https://vertex.daac.asf.alaska.edu/, and processed using the geographical information system software, ArcGIS version 10.0. The lithological database was provided by the Ministry of Environment, Carabobo State. 2) *Identification of the land uses in the La Guacamaya aquifer, Municipality of Valencia, Carabobo State*. Landsat satellite image was processed using the ArcGIS software by classifying in three types of uses and covers: 1) urban, 2) vegetation, and 3) deforested soil. *3) Determination of the hydraulic parameters of the La Guacamaya aquifer, Valencia Municipality, Carabobo State.* The Ministry of Environment provided information on static and dynamic levels; which was combined with level measurements made in 7 pumping wells of water for human consumption and industrial uses from the University of Carabobo using a mobile water level sensor for deep wells made by SEBA-Hydrometrie, 4) *Estimation of the physicochemical parameters of groundwater sources.* To obtain these data, water samples were collected in the 7 monitoring wells and processed by the Hidrolab Toro laboratory, determining the following physico-chemical parameters: Benzene, Toluene and o-Xylene. As a sample, the monitoring station 1 by the University of Carabobo (UC-1) is located in the coordinates: N10°09'18.6" and W68°01'53.6" (Table 1). *5) Simulation of the pollution plume for contaminants of the La Guacamaya aquifer*. The results were obtained by applying of the groundwater tool contained in the GIS software ArcGIS version 10.0.

In this study, three characteristics are presented with respect to the La Guacamaya aquifer: 1) physical, 2) chemicals, 3) hydraulics. In the first, the physical characteristics are represented in maps (Figure 2 and Figure 3): 1) terrain elevation, 2) terrain slope, 3) geology, 4) geomorphology, 5) stream orders, 6) Land use / Land cover. In the second, the combined database of hydrocarbons measured in soil and water provided by

Geohidra, 2017 and Rodriguez, 2018 is used to adjust geostatistical models from deterministic methods based on global and local polynomial interpolation in order to make spatial distribution prediction of the hydrocarbons in La Guacamaya aquifer using the geostatistical analyst tool of ArcGIS v10.0 (Figure 4 to Figure 10). In the third, the hydraulic characteristics are represented in maps (Figure 11): 1) water static level, 2) dynamic level, 3) hydraulic gradient, 4) saturated thickness, 5) flow velocity, and 6) flow discharge. Finally, a remediation proposal is included using the information on the three characteristics indicated before, equation of mass balance and equation linked to mass transfer process from liquid to gas media using the equation proposed by Sherwood and Holloway, (1940). These components are used to design a system of air injection and vapor extraction from soil.

Table: 1. *Localization of monitoring wells in a Carabobo State aquifer, Venezuela*

N°	Identification	North	West	Elevation (masl)
1	PM-1	10 09 31.4	68 01 26.9	468.96
2	PM-2	10 09 32.3	68 01 25.0	468.86
3	PM-3	10 09 33.9	68 01 26.9	469.78
4	PM-4	10 09 31.7	68 01 31.7	469.45
5	PM-5	10 09 32.3	68 01 26.1	469.11
6	PM-6	10 09 29.7	68 01 25.1	467.46
7	PM-7	10 09 29.4	68 01 29.7	467.88
8	PM-8	10 09 30.8	68 01 27.5	468.62
9	PM-9	10 09 32.3	68 01 27.0	469.18
10	PM-10	10 09 31.4	68 01 26.3	468.79
11	PM-11	10 09 31.8	68 01 25.7	468.88
12	PM-12	10 09 32.2	68 01 23.1	469.14
13	PM-13	10 09 26.6	68 01 30.3	466.94
14	PM-14	10 09 28.3	68 01 22.2	464.51
15	PM-15	10 09 28.7	68 01 27.3	468.72
16	UC-01	10 09 18.6	68 01 53.6	492
17	UC-02	10 09 08.3	68 02 04.8	475
18	UC-03	10 09 31.1	68 01 15.8	491
19	UC-04	10 09 29.3	68 01 36.3	408
20	UC-05	10 09 28.8	68 01 22.9	480
21	UC-06	10 09 34.0	68 01 25.7	472
22	UC-07	10 08 53.5	68 01 33.2	464

PM: monitoring well developed by Geohidra, (2017) for a study of Petroleum of Venezuela, S.A. (PDVSA), UC: monitoring wells operating for human consumption and industrial uses, which were measured by Rodriguez, (2018) for a study of Science Master of University of Carabobo.

RESULTS

The physical characteristics in a Carabobo State aquifer indicating monitoring wells are shown in Figure 2 and Table 2: a) Terrain Elevation (Figure 2a, Table 2) varies between 432 and 734 masl, most of the area of aquifer corresponding to 56% is located in terrain surface elevations varying between 412 and 438 masl, the monitoring wells are located between 439 and 469 masl, b) Terrain slope (Figure 2b, Table 2) varies between 0 and 104%, most of the area of aquifer corresponding to 57% is located in terrain slope varying between 0 and 4.47%, the monitoring wells are located between 5 and 14%, c) Geology (Figure 2c, Table 2) are constituted of two components: La Costa metamorphic suite (14.05%) and alluvial quaternary (85.94%), the monitoring wells are located in the alluvial quaternary, d) Geomorphology (Figure 2d, Table 2) are constituted of six components: 1) floodplain (15.27%), 2) alluvial plain (29.86%), 3) high plateau (43.12%), 4) stream valley (0.64%), 5) piedmont (9.58%) and 6) hill (1.50%). The monitoring wells are located in the alluvial plain. The stream order (Figure 2e, Table 2) is classified in three levels according to the stream division. The streams of order 1 have a total length of 18275.06 m, the streams of order 2 of 7512.19 m, the streams of order 3 of 5912.72 m. The monitoring wells are located near of stream of order 1. The land cover and land use is classified in 1) vegetation (35.69%), 2) deforested soil (2.31%) and 3) urban (62.09%). The monitoring wells are located in the urban area. The lithological profiles shown in Figure 3 indicate that there are alternating layers of clay of low plasticity with well graded sand; corresponding to confined aquifer.

The statistics of chemical characteristics measured in soil samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela, are shown in Table 3, Figure 4, as sample the minimum and maximum values are extracted: a) Total Petroleum Hydrocarbons (TPH) varies between 40 and 6000 mg/kg, b) TPH GRO (C_6-C_{10}) (GRO: Gasoline Range Organics) varies between 0.005 and 142.6 mg/kg, TPH DRO (C_{10}-C_{16}) (DRO: Diesel Range Organics) varies between 0.5 and 18.8 mg/kg, TPH DRO (C_{16}-C_{35}) varies between 0.2 and 114.5 mg/kg, TPH ORO (ORO: Oil Range Organics) varies between 12.2 and 327.8 mg/kg, Lead (Pb) varies between 5 and 129 mg/kg, c) BTEX: B: Benzene varies between 0.005 and 1.23 mg/kg, T: Toluene varies between 0.005 and 2.07 mg/kg, E: Ethylbenzene varies between 0.2 and 1.09 mg/kg, and metha-Xylene varies between 0.005 and 2.614 mg/kg, ortho- Xylene varies between 0.005 and 0.97 mg/kg, MTBE: Methyl Tertiary-Butyl Ether varies between 0.2 and 3.281 mg/kg. The box diagrams are overlapped indicating that there is not statistically significant difference between the set of values of TPH and congeners and Lead; likewise between BTEX and MTBE. There are atypical values, as a sample the value of 6000 mg/kg for the TPH measured in soil (Figure 4a). The atypical values vary between 2 and 4 times of values observed to 75% of total data set.

The statistics of chemical characteristics measured in water samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela, are shown in Table 4, Figure 5, as sample the minimum and maximum values are extracted: a) Total Petroleum Hydrocarbons (TPH) varies between 0.1 and 2.3 mg/l, b) TPH GRO (C_6-C_{10}) varies between 0.005 and 679.14 mg/l, TPH DRO (C_{10}-C_{16}) varies between 0.1 and 2.2 mg/l, TPH DRO (C_{16}-C_{35}) varies between 0.1 and 6.4 mg/l, TPH ORO varies between 0.1 and 7.3 mg/l, Lead (Pb) is of 0.1 mg/l, c) BTEX: B: Benzene varies between 0.05 and 159223 µg/l, T: Toluene varies between 0.005 and 44850.0 µg/l, E: Ethylbenzene varies between 0.057 and 5130 µg/l, and metha-Xylene varies between 0.062 and 17800.0 µg/l, ortho- Xylene varies between 0.011 and 4830.0 µg/l, MTBE: Methyl Tertiary-Butyl Ether varies between 0.273 and 570593 µg/l. The box diagrams are overlapped indicating that there is not statistically significant difference between the set of values of TPH and congeners and Lead; likewise between BTEX and MTBE. There are atypical values, as a sample the value of 6000 mg/kg for the TPH measured in soil. There are atypical values, as a sample the value of 600 mg/l for the TPH GRO measured in water (Figure 5a). The atypical values vary between 2 and 4 times of values observed to 75% of total data set.

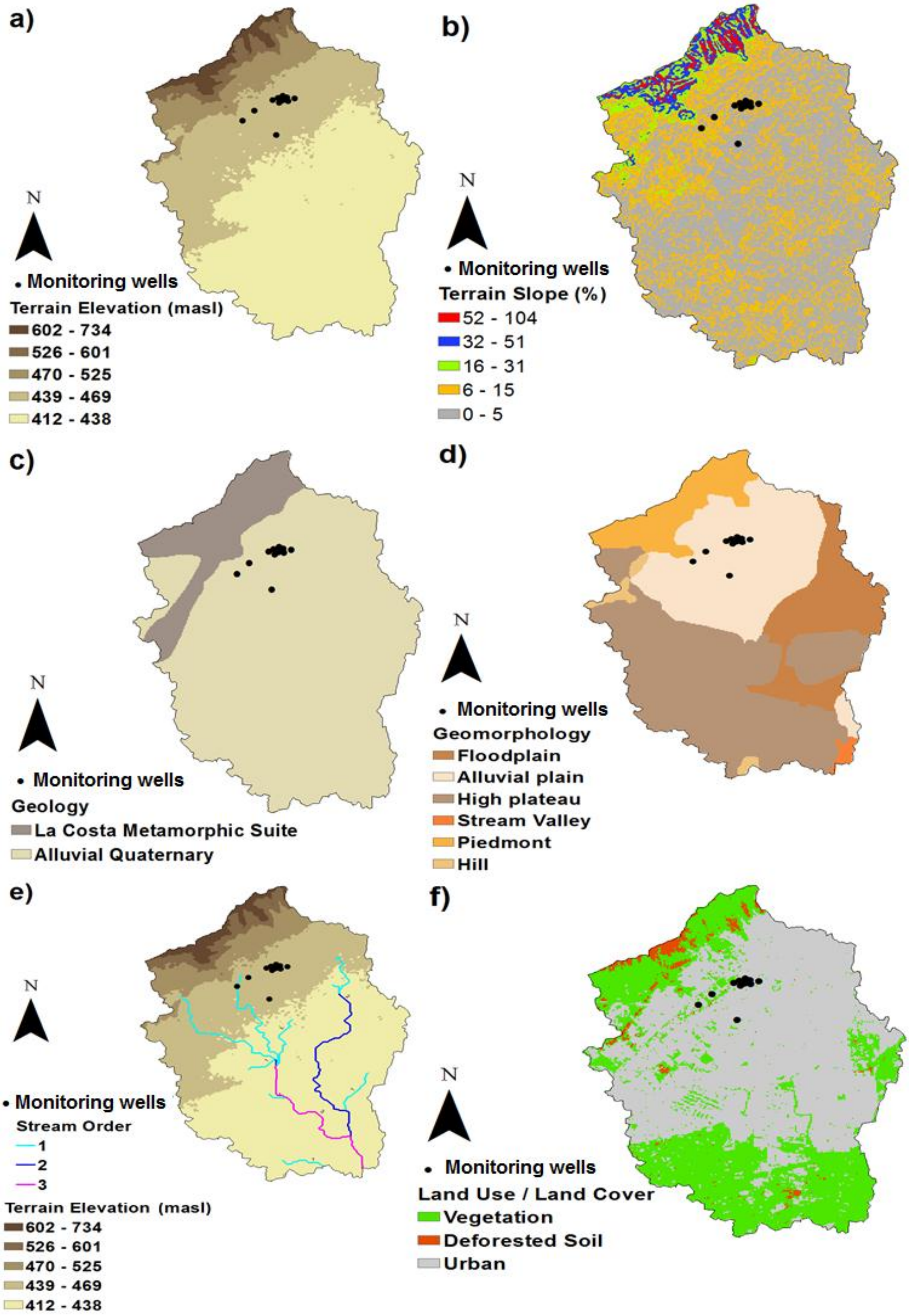
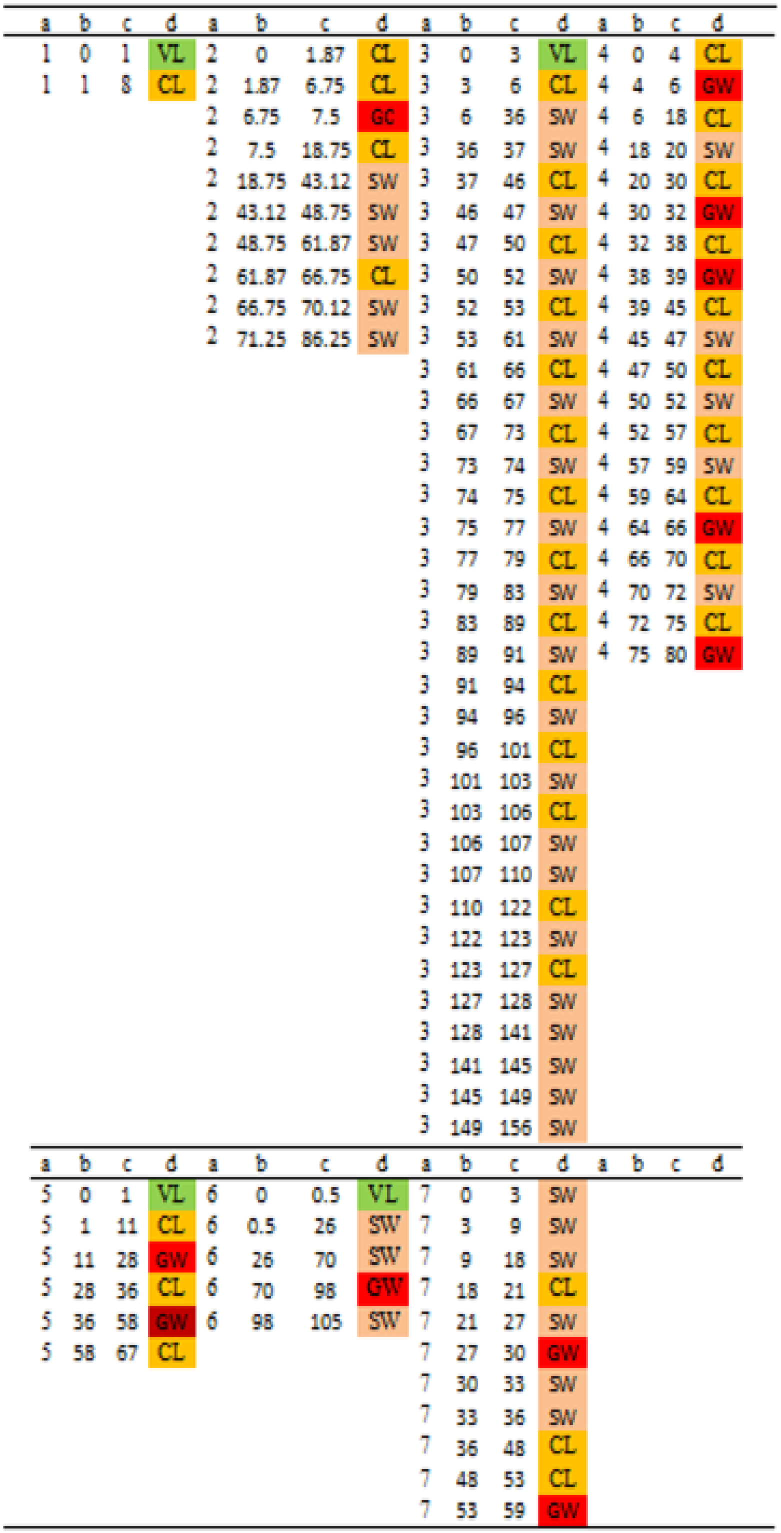


***Fig: 2.** Physical characteristics in a Carabobo State aquifer indicating monitoring wells: a) Terrain Elevation, b) Terrain slope, c) Geology, d) Geomorphology, e) Stream Order, f) Land Use/Land Cover*



a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
1	0	1	VL	2	0	1.87	CL	3	0	3	VL	4	0	4	CL
1	1	8	CL	2	1.87	6.75	CL	3	3	6	CL	4	4	6	GW
				2	6.75	7.5	GC	3	6	36	SW	4	6	18	CL
				2	7.5	18.75	CL	3	36	37	SW	4	18	20	SW
				2	18.75	43.12	SW	3	37	46	CL	4	20	30	CL
				2	43.12	48.75	SW	3	46	47	SW	4	30	32	GW
				2	48.75	61.87	SW	3	47	50	CL	4	32	38	CL
				2	61.87	66.75	CL	3	50	52	SW	4	38	39	GW
				2	66.75	70.12	SW	3	52	53	CL	4	39	45	CL
				2	71.25	86.25	SW	3	53	61	SW	4	45	47	SW
								3	61	66	CL	4	47	50	CL
								3	66	67	SW	4	50	52	SW
								3	67	73	CL	4	52	57	CL
								3	73	74	SW	4	57	59	SW
								3	74	75	CL	4	59	64	CL
								3	75	77	SW	4	64	66	GW
								3	77	79	CL	4	66	70	CL
								3	79	83	SW	4	70	72	SW
								3	83	89	CL	4	72	75	CL
								3	89	91	SW	4	75	80	GW
								3	91	94	CL				
								3	94	96	SW				
								3	96	101	CL				
								3	101	103	SW				
								3	103	106	CL				
								3	106	107	SW				
								3	107	110	SW				
								3	110	122	CL				
								3	122	123	SW				
								3	123	127	CL				
								3	127	128	SW				
								3	128	141	SW				
								3	141	145	SW				
								3	145	149	SW				
								3	149	156	SW				

a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
5	0	1	VL	6	0	0.5	VL	7	0	3	SW				
5	1	11	CL	6	0.5	26	SW	7	3	9	SW				
5	11	28	GW	6	26	70	SW	7	9	18	SW				
5	28	36	CL	6	70	98	GW	7	18	21	CL				
5	36	58	GW	6	98	105	SW	7	21	27	SW				
5	58	67	CL					7	27	30	GW				
								7	30	33	SW				
								7	33	36	SW				
								7	36	48	CL				
								7	48	53	CL				
								7	53	59	GW				

Fig: 3. *Lithological profiles in a Carabobo State aquifer, Venezuela. a: number of lithological profile, b: upper limit of layer, c: lower limit of layer, d: soil type in the layer. The type of soil corresponds to the Unified Soil Classification System (USCS) as: GW: well-graded gravel, GC: clayey gravel, GM: silty gravel, SW: well-graded sand, SM: silty sand, SC: clayey sand, CL: clay of low plasticity, ML: silt, VL: vegetation layer, R: Rock.*

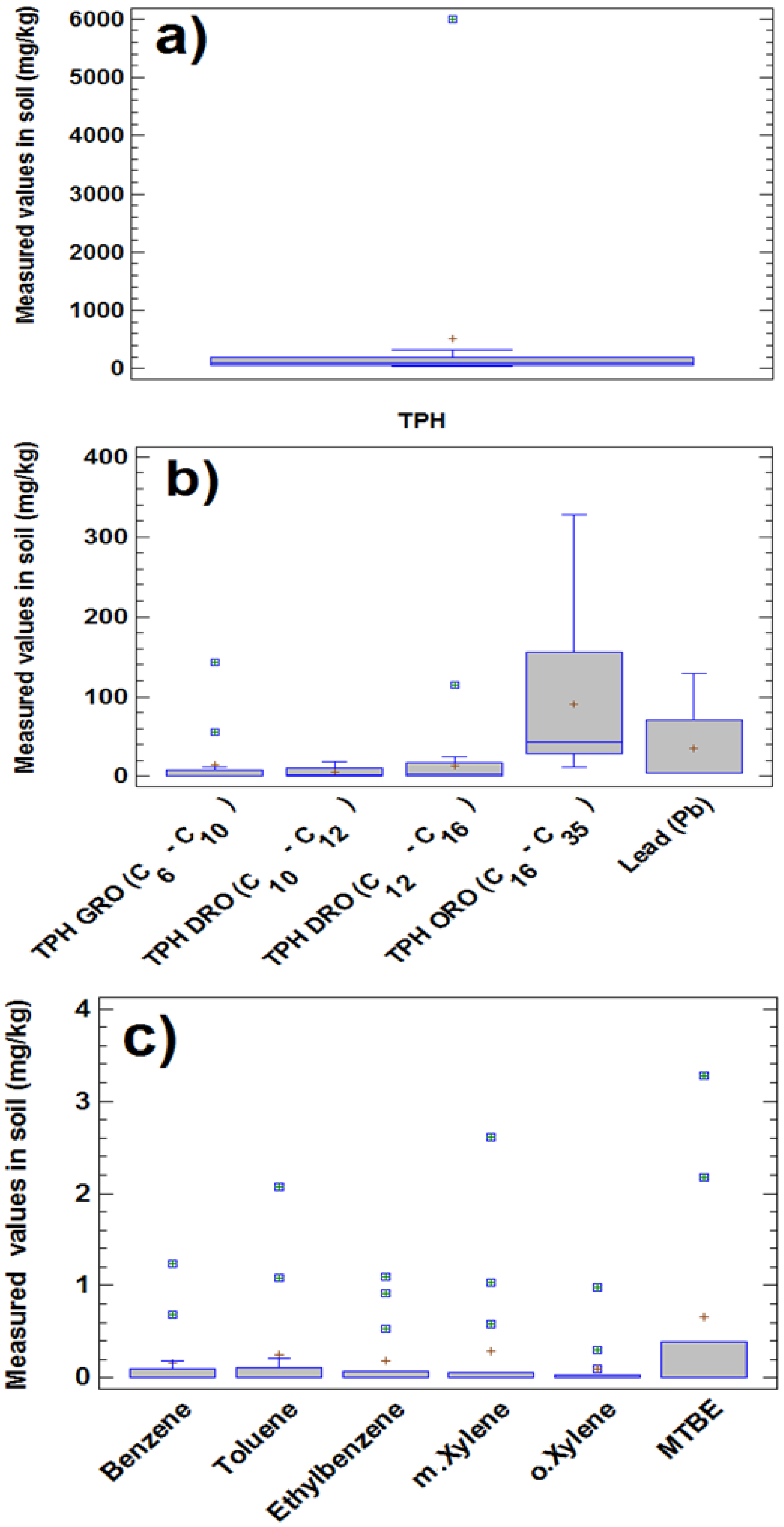


Fig: 4. *Chemical characteristics measured in soil samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela: a) Total Petroleum Hydrocarbons (TPH), b) TPH GRO (C_6-C_{10}) (GRO: Gasoline Range Organics), TPH DRO (C_{10}-C_{16}) (DRO: Diesel Range Organics), TPH DRO (C_{16}-C_{35}), TPH ORO (ORO: Oil Range Organics), Lead (Pb), c) BTEX: B: Benzene, T: Toluene, E: Ethylbenzene and X: Xylene (metha-Xylene, ortho- Xylene), MTBE: Methyl Tertiary-Butyl Ether*

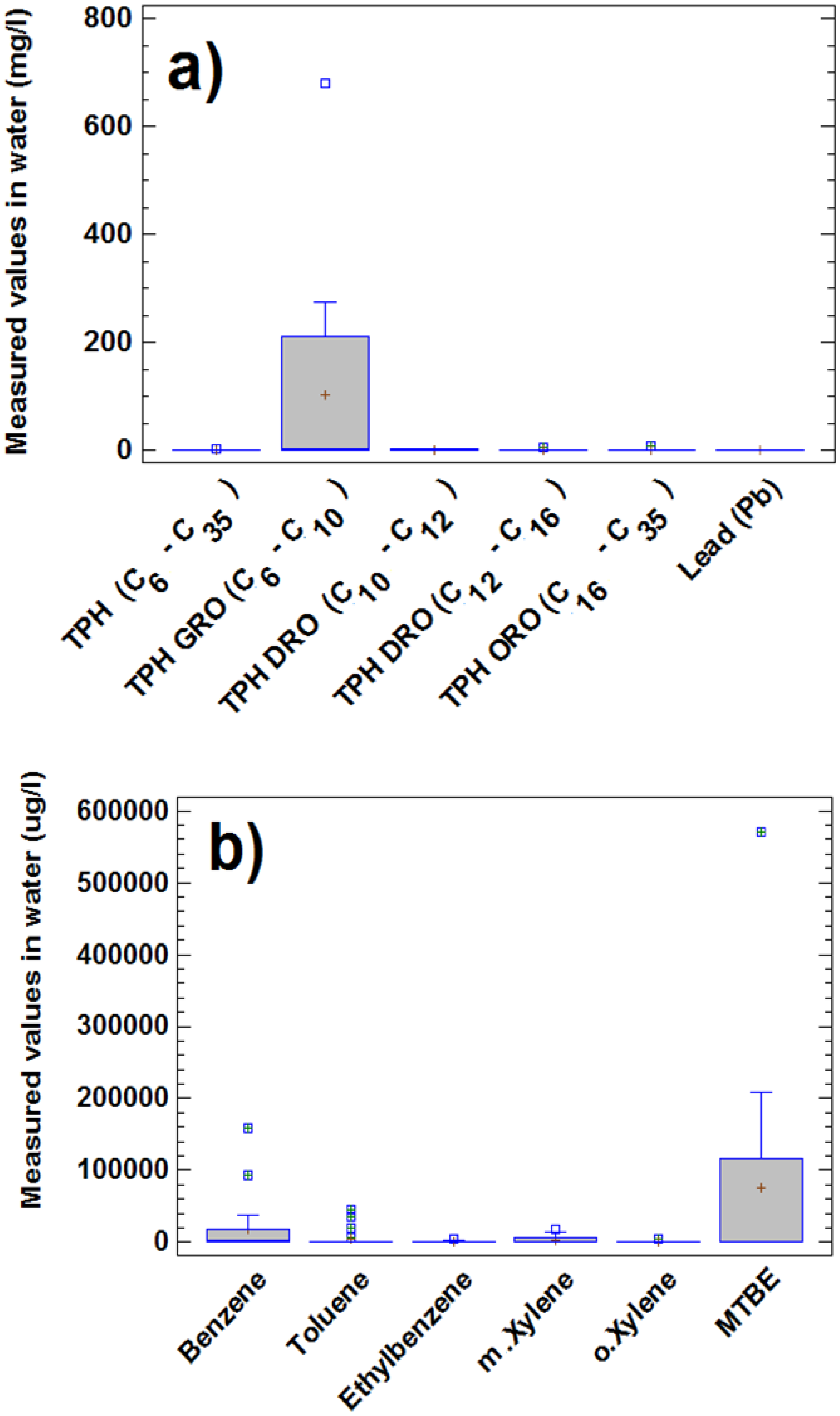


Fig: 5. *Chemical characteristics measured in water samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela: a) Total Petroleum Hydrocarbons (TPH), b) TPH GRO (C_6-C_{10}) (GRO: Gasoline Range Organics), TPH DRO (C_{10}-C_{16}) (DRO: Diesel Range Organics), TPH DRO (C_{16}-C_{35}), TPH ORO (ORO: Oil Range Organics), Lead (Pb)*

Table: 2. *Physical characteristics in a Carabobo State aquifer indicating monitoring wells: a) Terrain Elevation, b) Terrain slope, c) Geology, d) Geomorphology, e) Stream Order, f) Land Use/Land Cover*

Unit N°	Minimum	Maximum	Area (m^2)	Percentage of area	Length(m)
Terrain elevation (masl)					
1	412	438	30724530	56.17	
2	439	469	15811560	28.90	
3	470	525	4451406	8.14	
4	526	601	2144531	3.92	
5	602	734	1571563	2.87	
Terrain slope (%)					
1	0	4.472136	31531410	57.64	
2	5.09902	14.56022	17988750	32.88	
3	14.76482	31.01612	2519219	4.61	
4	31.04835	50.59644	1849531	3.38	
5	50.63596	104.0865	814687.5	1.49	
Geology					
1			621472500	14.05	
2			3799290000	85.94	
Geomorphology					
1			675345000	15.27	
2			1320247500	29.86	
3			1906245000	43.12	
4			28545000	0.64	
5			423637500	9.58	
6			66742500	1.50	
Stream Order					
1					18275.06
2					7512.19
3					5912.72
Land use /Land cover					
1			19478700	35.59	
2			1266300	2.31	
3			33984000	62.09	

Table: 3. *Statistics of chemical characteristics measured in soil samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela: a) Total Petroleum Hydrocarbons (TPH), b) TPH GRO (C_6-C_{10}) (GRO: Gasoline Range Organics), TPH DRO (C_{10}-C_{16}) (DRO: Diesel Range Organics), TPH DRO (C_{16}-C_{35}), TPH ORO (ORO: Oil Range Organics), Lead (Pb), c) BTEX: B: Benzene, T: Toluene, E: Ethylbenzene and X: Xylene (metha-Xylene, ortho- Xylene), MTBE: Methyl Tertiary-Butyl Ether*

	Unit	Count	Average	Standard deviation	Coeff. of variation	Minimum	Maximum
TPH	mg/kg	15	509.707	1521.13	298.432%	40.0	6000.0
TPH GRO (C_6-C_{10})	mg/kg	15	15.2552	38.0223	249.241%	0.005	142.6
TPH DRO (C_{10}-C_{12})	mg/kg	15	5.16667	6.57459	127.25%	0.5	18.8
TPH DRO (C_{12}-C_{16})	mg/kg	15	13.6733	28.9309	211.586%	0.2	114.5
TPH ORO (C_{16}-C_{35})	mg/kg	15	90.3067	88.4461	97.9397%	12.2	327.8
Lead (Pb)	mg/kg	15	34.8667	40.951	117.45%	5.0	129.0
Benzene	mg/kg	15	0.158333	0.345033	217.915%	0.005	1.234
Toluene	mg/kg	15	0.2436	0.574957	236.025%	0.005	2.072
Ethylbenzene	mg/kg	15	0.182333	0.361731	198.39%	0.005	1.097
m.Xylene	mg/kg	15	0.289667	0.706394	243.864%	0.005	2.614
o.Xylene	mg/kg	15	0.0974	0.25546	262.279%	0.005	0.978
MTBE	mg/kg	15	0.660633	1.19642	181.102%	0.005	3.281

Table: 4. *Statistics of chemical characteristics measured in water samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela: a) Total Petroleum Hydrocarbons (TPH), b) TPH GRO (C_6-C_{10}) (GRO: Gasoline Range Organics), TPH DRO (C_{10}-C_{16}) (DRO: Diesel Range Organics), TPH DRO (C_{16}-C_{35}), TPH ORO (ORO: Oil Range Organics), Lead (Pb), c) BTEX: B: Benzene, T: Toluene, E: Ethylbenzene and X: Xylene (metha-Xylene, ortho- Xylene), MTBE: Methyl Tertiary-Butyl Ether*

	Unit	Count	Average	Standard deviation	Coeff. of variation	Minimum	Maximum
TPH (C_6 - C_{35})	mg/l	15	0.506667	0.568792	112.261%	0.1	2.3
TPH GRO (C_6 - C_{10})	mg/l	15	103.035	189.753	184.164%	0.005	679.14
TPH DRO (C_{10} - C_{12})	mg/l	15	0.72	0.824794	114.555%	0.1	2.2
TPH DRO (C_{12} - C_{16})	mg/l	15	0.66	1.60704	243.491%	0.1	6.4
TPH ORO (C_{16} - C_{35})	mg/l	15	0.773333	1.81402	234.571%	0.1	7.3
Lead (Pb)	mg/l	15	0.1	0	0%	0.1	0.1
Benzene	µg/l	22	18127.3	37977.2	209.502%	0.05	159223.
Toluene	µg/l	22	4987.13	12304.7	246.729%	0.05	44850.0
Ethylbenzene	µg/l	15	736.948	1407.42	190.98%	0.057	5130.0
m.Xylene	µg/l	15	3148.91	5637.32	179.024%	0.062	17800.0
o.Xylene	µg/l	19	805.805	1649.16	204.66%	0.011	4830.0
MTBE	µg/l	15	76111.3	153631.	201.85%	0.273	570593.

The spatial prediction of chemical characteristics measured in soil samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela, are shown in Figure 6 and Table 5: *a) Total Petroleum Hydrocarbons (TPH):* the source of maximum contamination is close to the monitoring stations PM-4, PM-9 and PM-12. This spatial prediction is explained by a local polynomial interpolation with order 3, Kernell function of Epanechnikov and a gradient of linear regression function of 0.28 *b) TPH GRO (C_6-C_{10})* the source of maximum contamination is close to the monitoring stations PM-4, and PM-7. This spatial prediction is explained by a local polynomial interpolation with order 3, Kernell function of Quartic and a gradient of linear regression function of 0.59, *c) TPH DRO (C_{10}-C_{16})* the source of maximum contamination is close to the monitoring stations PM-4, and PM-7. This spatial prediction is explained by a local polynomial interpolation with order 2, Kernell function of Polynomial order 5 and a gradient of linear regression function of 0.67, *d) TPH DRO (C_{16}-C_{35})* the source of maximum contamination is close to the monitoring stations PM-4, and PM-9. This spatial prediction is explained by a local polynomial interpolation with order 3, Kernell function of Exponential and a gradient of linear regression function of 0.80, e) *TPH ORO* the source of maximum contamination is close to the monitoring stations PM-4, and PM-12. This spatial prediction is explained by a local polynomial interpolation with order 3, Kernell function of Gaussian and a gradient of linear regression function of 0.80, f) *Lead (Pb)* the source of maximum contamination is close to the monitoring stations PM-4, PM-3 and PM-12. This spatial prediction is explained by a local polynomial interpolation with order 2, Kernell function of Epanechinov and a gradient of linear regression function of 0.94. The spatial prediction of chemical characteristics measured in soil samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela, are shown in Figure 7 and Table 5: BTEX: *a) Benzene:* the source of maximum contamination is close to the monitoring stations PM-6, PM13 and PM-15. This spatial prediction is explained by a local polynomial interpolation with order 3, Kernell function of Exponential and a gradient of linear regression function of 0.72, *b) Toluene* the source of maximum contamination is close to the monitoring stations PM-6, and PM-15. This spatial prediction is explained by a global polynomial interpolation with order 3 and a gradient of linear regression function of 0.94, *c) Ethylbenzene* the source of maximum contamination is close to the monitoring stations PM-6, PM-13, and PM-15, *d) metha-Xylene* the source of maximum contamination is close to the monitoring stations PM-6, PM-13 and PM-15. This spatial prediction is explained by a global polynomial interpolation with order 3 and a gradient of linear regression function of 0.93, *e) ortho- Xylene* the source of maximum contamination is close to the monitoring stations PM-6, PM13 and PM-15. This spatial prediction is explained by a local polynomial interpolation with order 3, Kernell function of Gaussian and a gradient of linear regression function of 0.72, f) *MTBE: Methyl Tertiary-Butyl Ether* the source of maximum contamination is close to the monitoring stations PM-6, PM13 and PM-15. This spatial prediction is explained by a global polynomial interpolation with order 2 and a gradient of linear regression function of 0.

Table: 5. *Statistics of spatial prediction using deterministic methods of chemical characteristics measured in soil samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela: a) Total Petroleum Hydrocarbons (TPH), b) TPH GRO (C_6-C_{10}) (GRO: Gasoline Range Organics), c)TPH DRO (C_{10}-C_{16}) (DRO: Diesel Range Organics), d) TPH DRO (C_{16}-C_{35}), e) TPH ORO (ORO: Oil Range Organics), f) Lead (Pb)*

Physico-Chemical Parameters	Unit	SSPM	Ordinary Kriging
TPH	**mg/kg**	DM	Local polynomial Interpolation
		OP	3
		KF	Epanechnikov
		PRF	0.28460520671002 * x + -1985.67972779922
TPH GRO (C_6-C_{10})	**mg/kg**	DM	Local polynomial Interpolation
		OP	3
		KF	Quartic
		PRF	0.592769642106749 * x + -87.7323506810128
TPH DRO (C_{10}-C_{12})	**mg/kg**	DM	Local polynomial Interpolation
		OP	2
		KF	Polynomial order 5
		PRF	0.671841146677751 * x + -1.76870993567521
TPH DRO (C_{12}-C_{16})	**mg/kg**	DM	Local polynomial Interpolation
		OP	3
		KF	Exponential
		PRF	0.804922181333584 * x + -26.8747504061333
TPH ORO (C_{16}-C_{35})	**mg/kg**	DM	Local polynomial Interpolation
		OP	3
		KF	Gaussian
		PRF	0.804922181333584 * x + -26.8747504061333
Lead	**mg/kg**	DM	Local polynomial Interpolation
		OP	2
		KF	Epanechnikov
		PRF	0.94409190209168 * x + 5.35687906663836
Benzene	**mg/kg**	DM	Local polynomial Interpolation
		OP	3
		KF	Exponential
		PRF	0.720555712 * x + -1.1334187876
Toluene	**mg/kg**	DM	Global polynomial Interpolation
		OP	3
		PRF	0.938500937909668 * x + -1.44489029786802
m.Xyelene	**mg/kg**	DM	Global polynomial Interpolation
		OP	3
		PRF	0.938500937909668 * x + -1.44489029786802
o.Xyelene	**mg/kg**	DM	Local polynomial Interpolation
		OP	3
		KF	Gaussian
		PRF	1.12097503729533 * x + -0.456425358301639
MTBE	**mg/kg**	DM	Global polynomial Interpolation
		OP	2
		PRF	0.348548847562566 * x + 0.29913467178114

OP: Order of polynomial, KF: Kernel Function, PRF: Predicted Regression Function

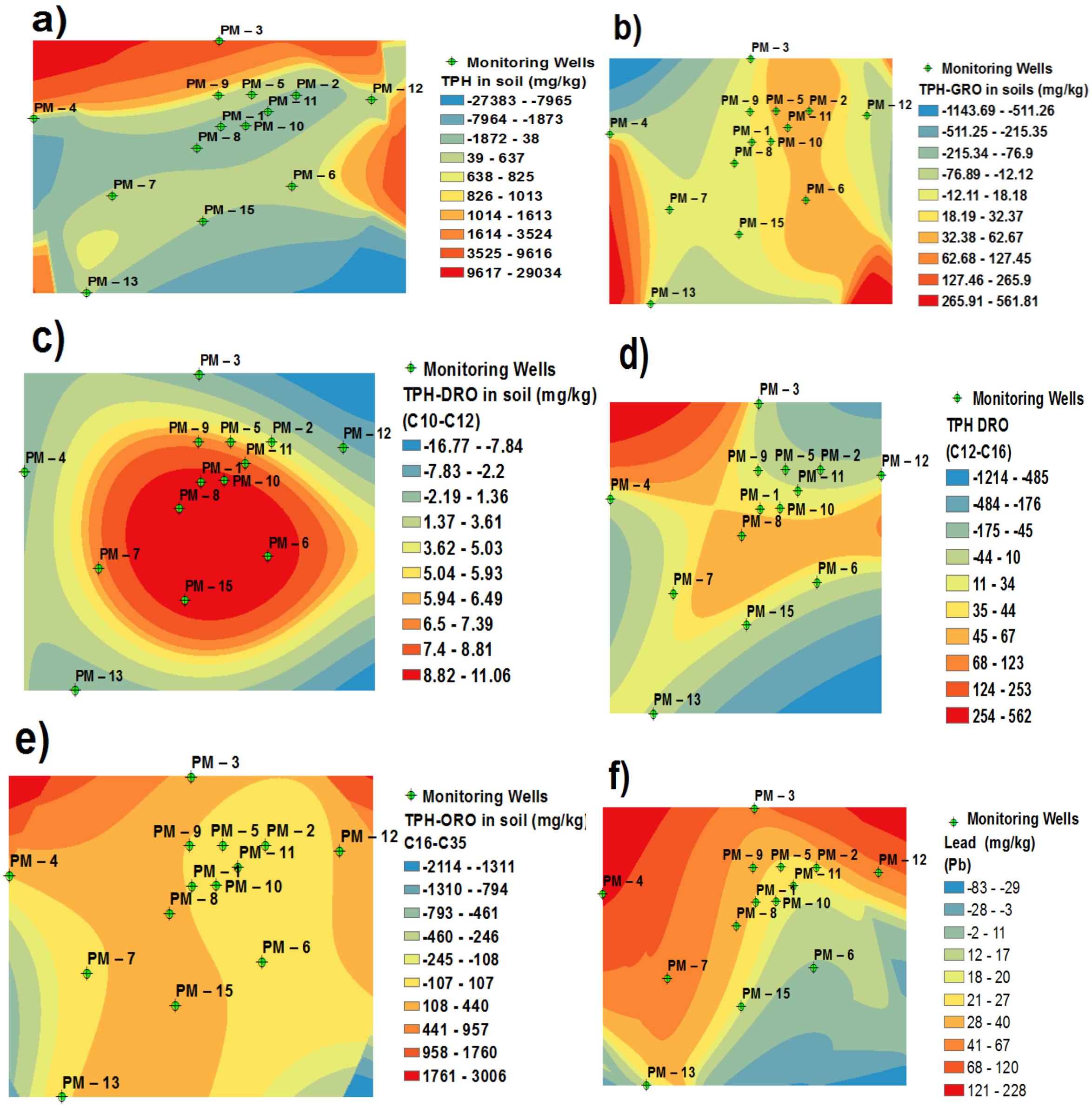


Fig: 6. *Spatial prediction of chemical characteristics measured in soil samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela: a) Total Petroleum Hydrocarbons (TPH), b) TPH GRO (C_6-C_{10}) (GRO: Gasoline Range Organics), c)TPH DRO (C_{10}-C_{16}) (DRO: Diesel Range Organics), d) TPH DRO (C_{16}-C_{35}), e) TPH ORO (ORO: Oil Range Organics), f) Lead (Pb)*

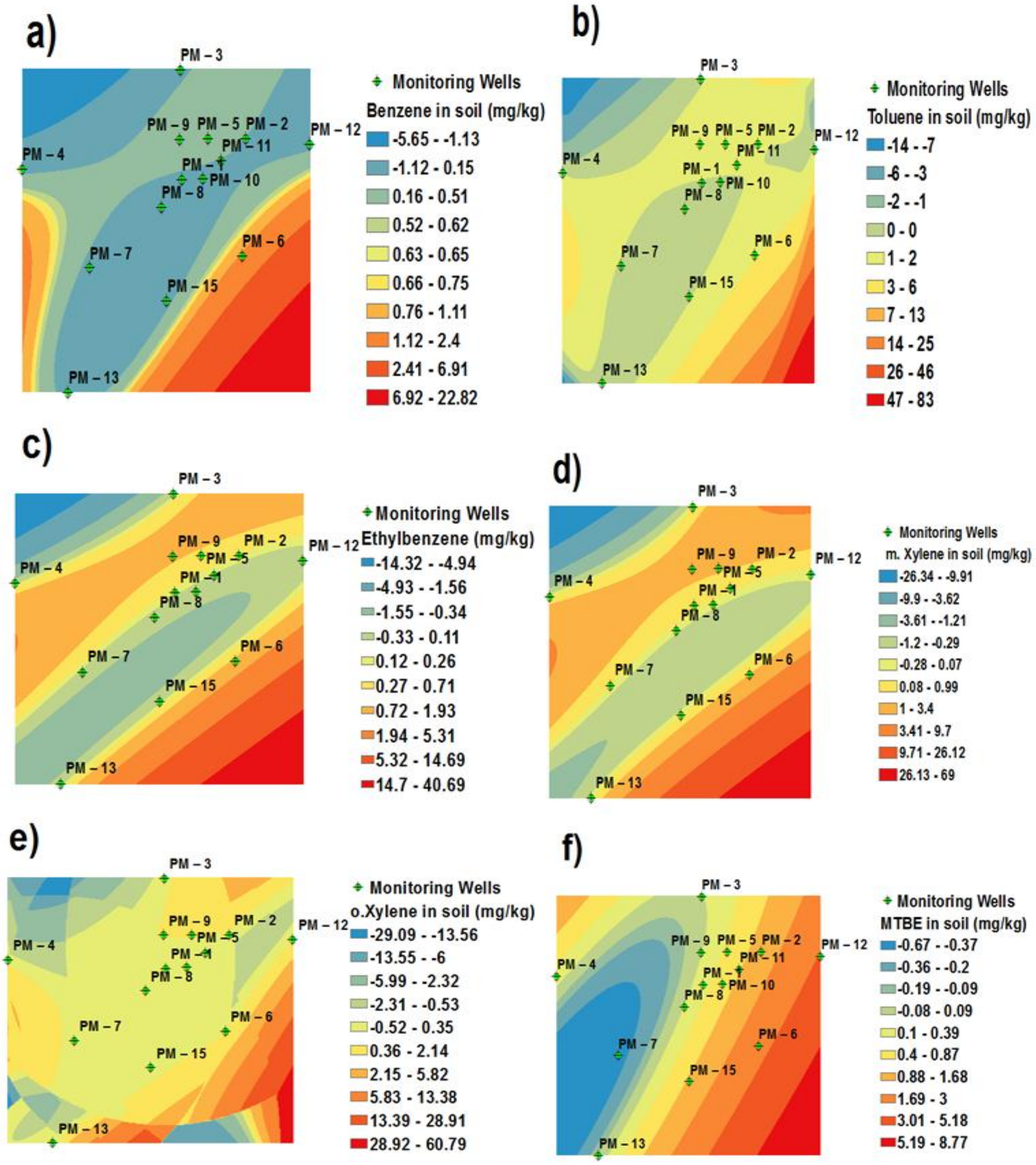


Fig: 7. *Spatial prediction of chemical characteristics measured in soil samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela: BTEX: a) Benzene, b) Toluene, c) Ethylbenzene d) metha-Xylene, e) ortho- Xylene , f) MTBE: Methyl Tertiary-Butyl Ether*

The spatial prediction of chemical characteristics measured in water samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela, are shown in Figure 8 and Table 6: *a) TPH* the source of maximum contamination is close to the monitoring stations PM-4, PM-6, PM-12 PM-15. This spatial prediction is explained by a local polynomial interpolation with order 3, Kernell function of Quartic order and a gradient of linear regression function of 0.39, *b) TPH GRO* (C_6-C_{10}) the source of maximum contamination is close to the monitoring stations PM-2, PM-7 and PM-15. This spatial prediction is explained by a local polynomial interpolation with order 2, Kernell function of Polynomial 5 order and a gradient of linear regression function of 0.56, *c) TPH DRO* (C_{10}-C_{16}) the source of maximum contamination is close to the monitoring stations PM-2, PM-7 and PM-15. This spatial prediction is explained by a local polynomial interpolation with order 2, Kernell function of Polynomial 5 order and a gradient of linear regression function of 0.57, *d) TPH DRO* (C_{16}-C_{35}) the source of maximum contamination is close to the monitoring stations PM-2, PM-7 and PM-15. This spatial prediction is explained by a local polynomial interpolation with order 3, Kernell function of Exponential and a gradient of linear regression function of 0.55, *e) TPH ORO* the source of maximum contamination is close to the monitoring stations PM-2, PM-7 and PM-15. This spatial prediction is explained by a local polynomial interpolation with order 2, Kernell function of Exponential and a gradient of linear regression function of 0.27.

The spatial prediction of chemical characteristics measured in water samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela, are shown in Figure 9 and Table 6: BTEX: *a) Benzene:* the source of maximum contamination is close to the monitoring stations PM-7, PM12 and PM-15. This spatial prediction is explained by a local polynomial interpolation with order 2, Kernell function of Polynomial 5 order and a gradient of linear regression function of 0.55, *b) Toluene* the source of maximum contamination is close to the monitoring stations PM-7, PM12 and PM-15. This spatial prediction is explained by a global polynomial interpolation with order 2 and a gradient of linear regression function of 0.41, *c) Ethylbenzene* the source of maximum contamination is close to the monitoring stations PM-7, PM12 and PM-15. *d) metha-Xylene* the source of maximum contamination is close to the monitoring stations PM-7, PM12 and PM-15. This spatial prediction is explained by a global polynomial interpolation with order 3 and a gradient of linear regression function of 1.44, *e) ortho- Xylene* the source of maximum contamination is close to the monitoring stations PM-7, PM12 and PM-15. This spatial prediction is explained by a local polynomial interpolation with order 2, Kernell function of Epanechnikov and a gradient of linear regression function of 0.41, f) *MTBE: Methyl Tertiary-Butyl Ether* the source of maximum contamination is close to the monitoring stations PM-7, PM12 and PM-15. This spatial prediction is explained by a local polynomial interpolation with order 2, Kernell function of Epanechnikov and a gradient of linear regression function of 0.62.

The statistics of spatial prediction of chemical characteristics measured in water samples extracted from 15 monitoring wells developed by PDVSA (Petroleos de Venezuela, S.A.) combined with the water samples extracted from 7 monitoring wells for domestic and industrial uses by the University of Carabobo in a Carabobo State aquifer, Venezuela, are shown in Figure 10 and Table 7: BTEX: a) Benzene the source of maximum contamination is close to the monitoring stations PM-1 to PM-15. This spatial prediction is explained by a local polynomial interpolation with order 2, Kernell function of Exponential and a gradient of linear regression function of 0.94, b) Toluene the source of maximum contamination is close to the monitoring stations PM-1 to PM-15. This spatial prediction is explained by a local polynomial interpolation with order 2, Kernell function of Exponential and a gradient of linear regression function of 0.94, c) ortho- Xylene the source of maximum contamination is close to the monitoring stations PM-1 to PM-15. This spatial prediction is explained by a local polynomial interpolation with order 2, Kernell function of Exponential and a gradient of linear regression function of 0.72.

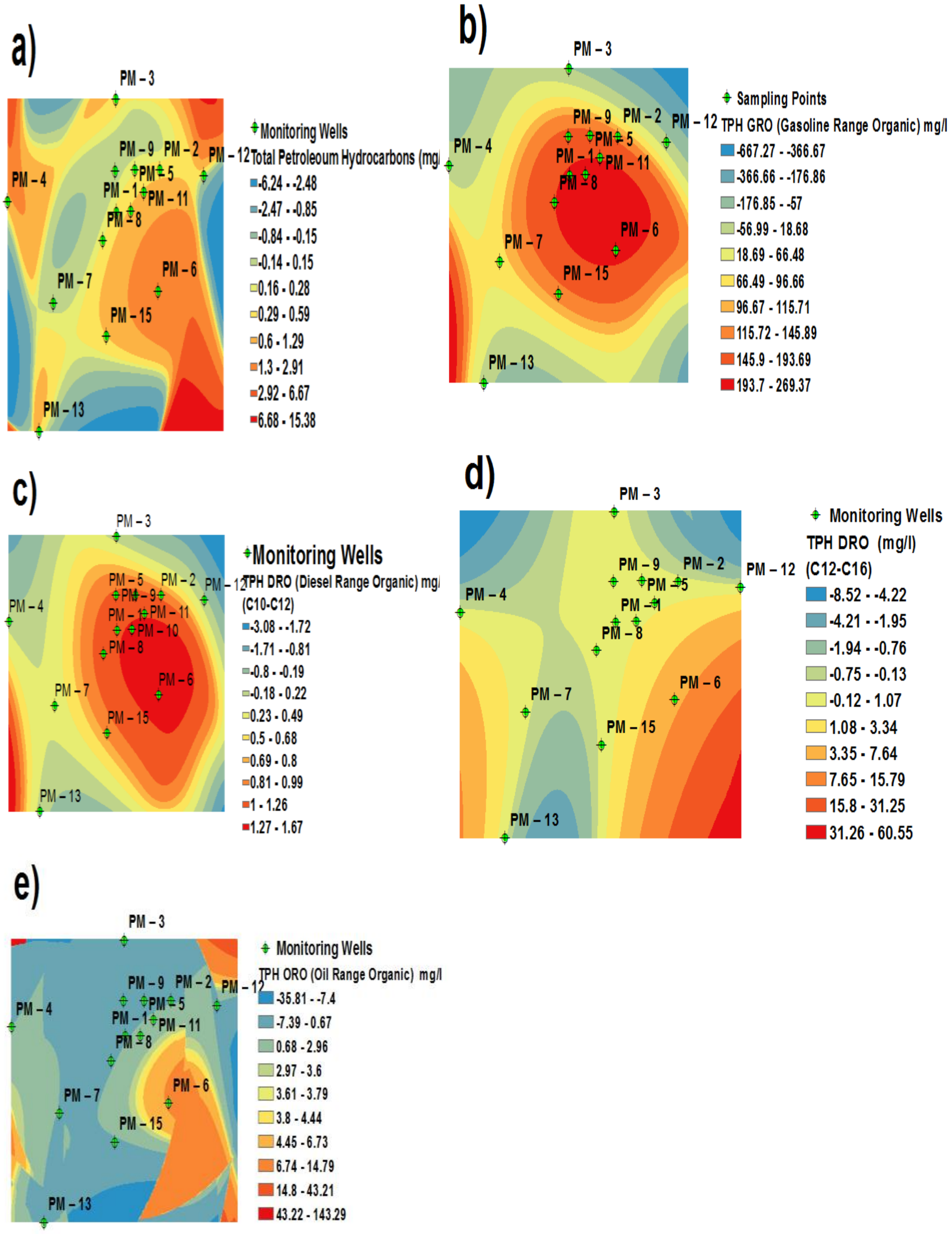


Fig: 8. *Spatial prediction of chemical characteristics measured in water samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela: a) Total Petroleum Hydrocarbons (TPH), b) TPH GRO (C_6-C_{10}) (GRO: Gasoline Range Organics), c)TPH DRO (C_{10}-C_{16}) (DRO: Diesel Range Organics), d) TPH DRO (C_{16}-C_{35}), e) TPH ORO (ORO: Oil Range Organics)*

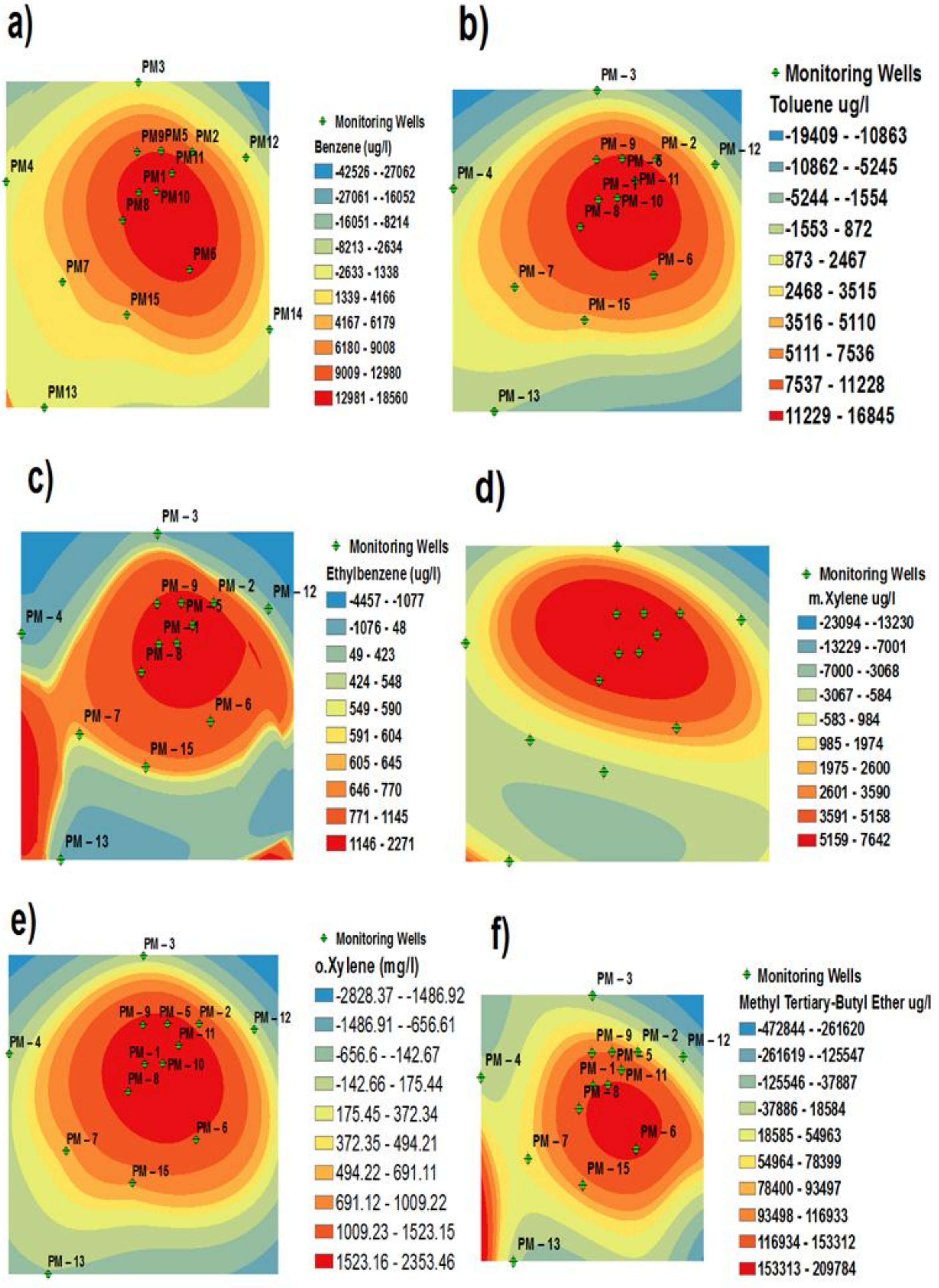


Fig: 9. *Spatial prediction of chemical characteristics measured in water samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela: BTEX: a) Benzene, b) Toluene, c) Ethylbenzene, d) metha-Xylene, e) ortho- Xylene , f) MTBE: Methyl Tertiary-Butyl Ether*

Table: 6. *Statistics of spatial prediction using deterministic methods of chemical characteristics measured in water samples extracted from 15 monitoring wells in a Carabobo State aquifer, Venezuela: a) Total Petroleum Hydrocarbons (TPH), b) TPH GRO (C_6-C_{10}) (GRO: Gasoline Range Organics), c)TPH DRO (C_{10}-C_{16}) (DRO: Diesel Range Organics), d) TPH DRO (C_{16}-C_{35}), e) TPH ORO (ORO: Oil Range Organics), f) Lead (Pb)*

Physico-Chemical Parameters	Unit	SSPM	Ordinary Kriging
TPH	**mg/l**	DM	Local polynomial Interpolation
		OP	3
		KF	Quartic
		PRF	0.393873326501493 * x + 1.41654438124167
TPH GRO (C_6-C_{10})	**mg/l**	DM	Local polynomial Interpolation
		OP	2
		KF	Polynomial 5 order
		PRF	0.562194612940361 * x + -83.961325297697
TPH DRO (C_{10}-C_{12})	**mg/l**	DM	Local polynomial Interpolation
		OP	2
		KF	Polynomial 5 order
		PRF	0.577097044129682 * x + 0.0695809554385322
TPH DRO (C_{12}-C_{16})	**mg/l**	DM	Local polynomial Interpolation
		OP	3
		KF	Exponential
		PRF	0.556762849317677 * x + -1.3256336761485
TPH ORO (C_{16}-C_{35})	**mg/l**	DM	Local polynomial Interpolation
		OP	3
		KF	Exponential
		PRF	0.270640968049954 * x + -1.86469971122671
Benzene	**mg/l**	DM	Local polynomial Interpolation
		OP	2
		KF	Polynomial 5 order
		PRF	0.557038097965685 * x + -2027.5095566665
Toluene	**mg/l**	DM	Local polynomial Interpolation
		OP	2
		KF	Exponential
		PRF	0.408504049756411 * x + -3666.53299941957
m.Xyelene	**mg/l**	DM	Global polynomial Interpolation
		OP	3
		PRF	1.44440406488439 * x + -12450.0031999271
o.Xyelene	**mg/l**	DM	Local polynomial Interpolation
		OP	2
		KF	Epanechnikov
		PRF	0.408504049756411 * x + -3666.53299941957
MTBE	**mg/l**	DM	Local polynomial Interpolation
		OP	2
		KF	Epanechnikov
		PRF	0.682614467587869 * x + -1203.50323913832

OP: Order of polynomial, KF: Kernel Function, PRF: Predicted Regression Function

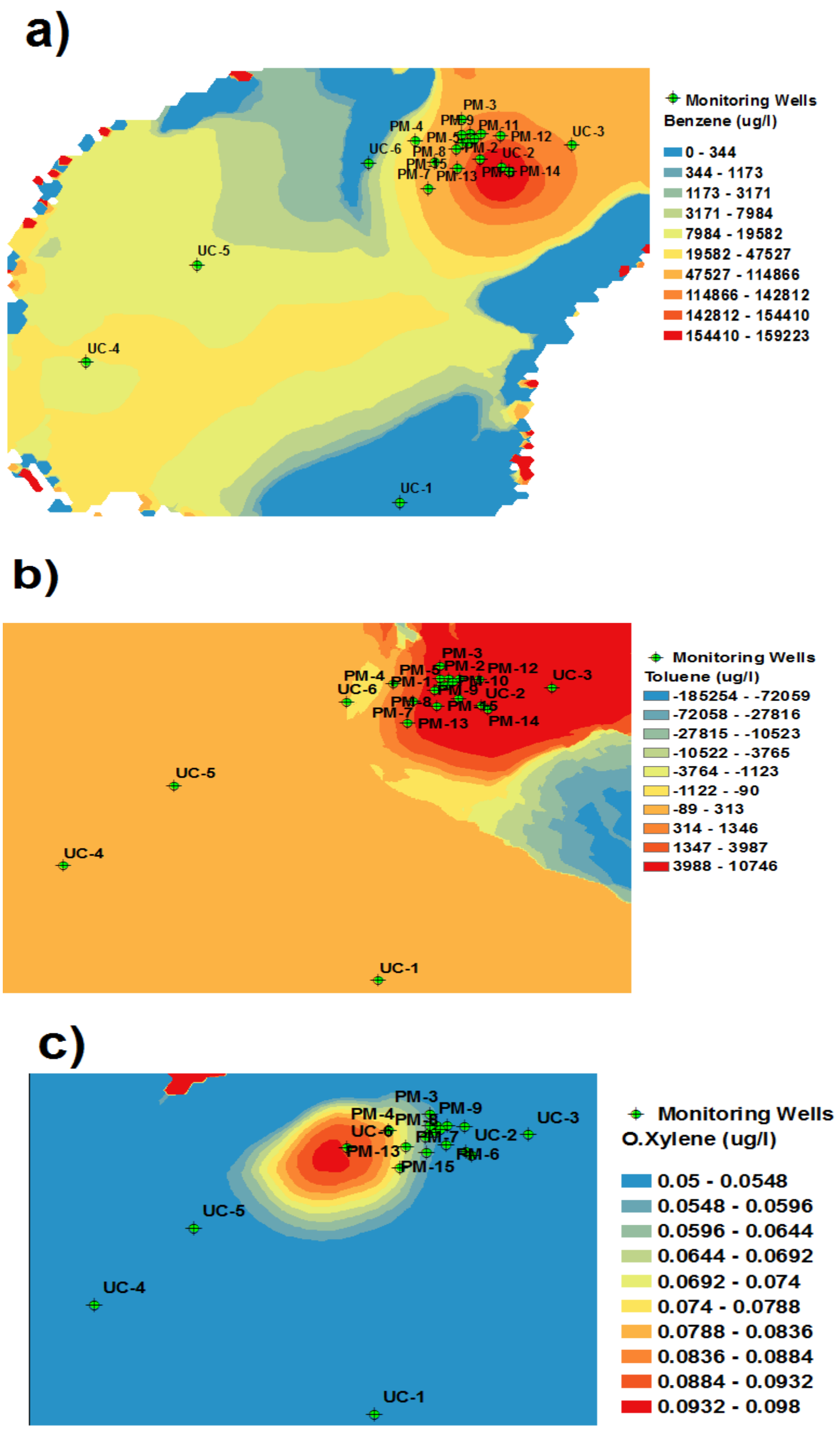


Fig: 10. *Spatial prediction of chemical characteristics measured in water samples extracted from 15 monitoring wells developed by PDVSA (Petroleos de Venezuela, S.A.) combined with the water samples extracted from 7 monitoring wells for domestic and industrial uses by the University of Carabobo in a Carabobo State aquifer, Venezuela: BTEX: a) Benzene, b) Toluene, c) Ethylbenzene*

Table: 7. *Statistics of spatial prediction of chemical characteristics measured in water samples extracted from 15 monitoring wells developed by PDVSA (Petroleos de Venezuela, S.A.) combined with the water samples extracted from 7 monitoring wells for domestic and industrial uses by the University of Carabobo in a Carabobo State aquifer, Venezuela: BTEX: a) Benzene, b) Toluene, c) ortho- Xylene*

Physico-Chemical Parameters	**Unit**	**SSPM**	**Ordinary Krigging**
Benzene	mg/l	DM	Local polynomial Interpolation
		OP	2
		KF	Exponential
		PRF	0.948897164056249 * x + 986.718386069828
Toluene	mg/l	DM	Local polynomial Interpolation
		OP	2
		KF	Exponential
		PRF	0.941560191957777 * x + 11.5130611412567
o. Xylene	mg/l	DM	Local polynomial Interpolation
		OP	2
		KF	Exponential
		PRF	0.723500847430219 * x + 0.0143122609235567

OP: Order of polynomial, KF: Kernel Function, PRF: Predicted Regression Function

Hydraulic parameters in a Carabobo State aquifer, Venezuela, are shown in Figure 11: a) Water static level, b) Water dynamic level, c) Hydraulic gradient, d) Saturated Thickness, e) Flow Velocity, f) Flow discharge: a) Water static level (Figure 11a, Table 8) varies between 407.62 and 686.10 masl, most of the area of aquifer corresponding to 57% is located in water static level varying between 407 and 433 masl, b) Water dynamic level (Figure 11b, Table 8) varies between 358.09 and 663.68 masl, most of the area of aquifer corresponding to 61.36% is located in Water dynamic levels varying between 358.09 and 663.78 masl, c) Hydraulic gradient (Figure 11c, Table 8) varies between 0.01 and 62.43 %, most of the area of aquifer corresponding to 68.17% is located in hydraulic gradient varying between 0.01 and 3.25%, d) Saturated Thickness, (Figure 11d, Table 8) varies between 35 and 99 m, most of the area of aquifer corresponding to 39.96% is located in saturated thickness varying between 45 and 54 m, e) Flow velocity, (Figure 11e, Table 8) varies between 0.03 and 84.14 m/d, most of the area of aquifer corresponding to 68.75% is located in flow velocity varying between 2.25 and 68.75 m/d, f) Flow discharge, (Figure 11f, Table 8) varies between 330 and 841405 m^3/d, most of the area of aquifer corresponding to 68.75% is located in flow discharge varying between 330 and 46339 m^3/d.

The mass flow in a Carabobo State aquifer, Venezuela, is shown in Figure 12: *BTEX: a) Benzene:* the maximum mass flow is 15837.1 kg/d, *b) Toluene:* the maximum mass flow is 557.31 kg/d, c) ortho- Xylene: the maximum mass flow is 0.156 kg/d.

The parameters for remediation applying air injection and vapor extraction in a Carabobo State aquifer, Venezuela, are shown in Table 9: *For Benzene:* the required air is 13153 m^3/d (323 cfm) and the vapor extraction is 5075 m^3/d (125 cfm). *For Toluene:* the required air is 463 m^3/d (11.35 cfm) and the vapor extraction is 6.28 m^3/d (3.7 cfm). *For O-Xylene:* the required air is 0.13 m^3/d (0.014 cfm) and the vapor extraction is 0.036 m^3/d (0.000882 cfm). The proposed wells for air injection (42) and vapor extraction (19) in a Carabobo State aquifer polluted with

Benzene separated each 100 meters and 150 meters, respectively are shown in Figure 13. The regulatory limit for the Benzene in water is 10 µg/l according to the Sanitary Standard for Drinking Water Quality, Official Gazette Venezuela. Nº 36395 Art. 14. The distribution of wells is valid for treatment of the rest of hydrocarbons referenced in Figures 8 and 9.

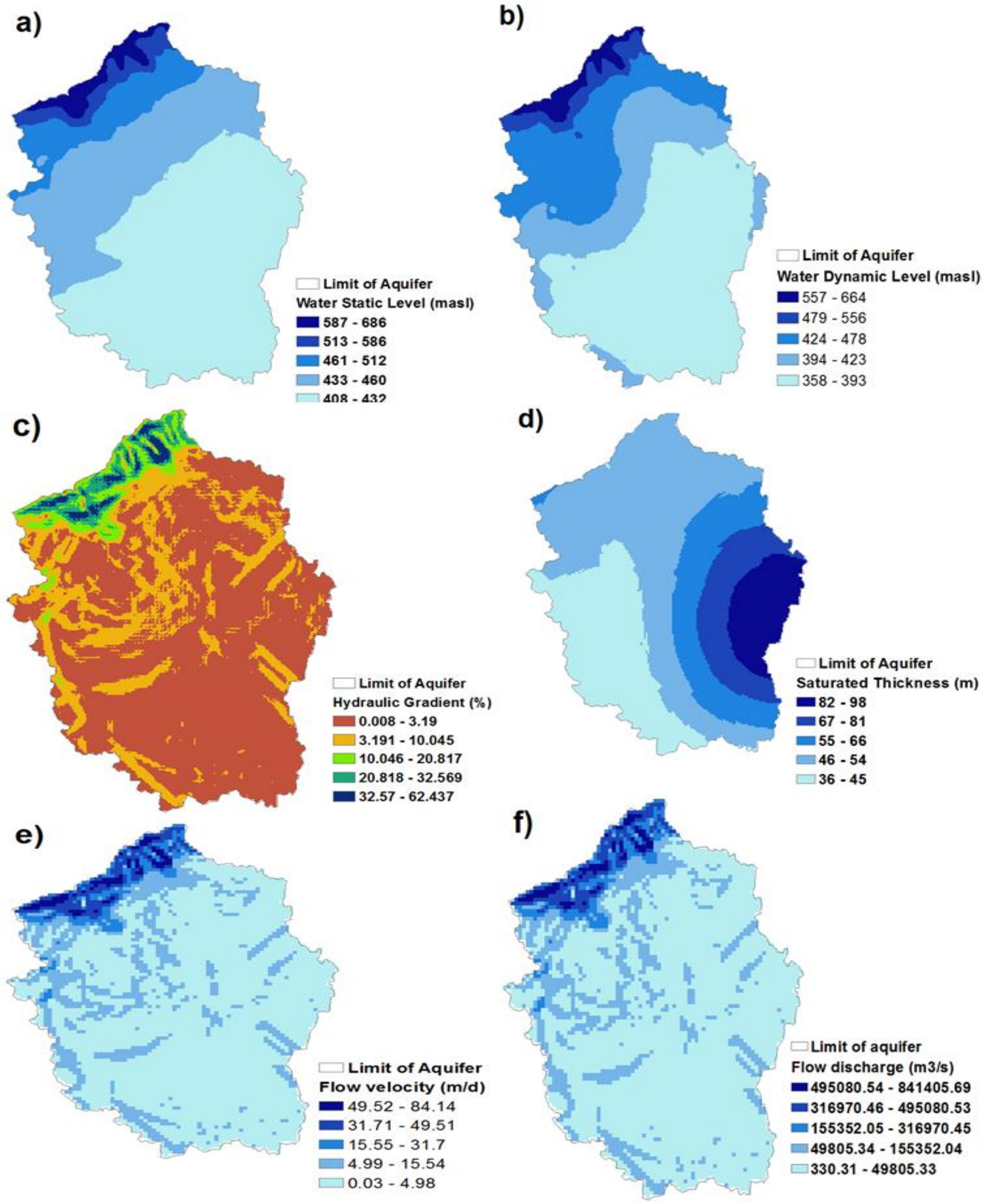


Fig: 11. *Hydraulic parameters in a Carabobo State aquifer, Venezuela: a) Water static level, b) Water dynamic level, c) Hydraulic gradient, d) Saturated Thickness, e) Flow Velocity, f) Flow discharge*

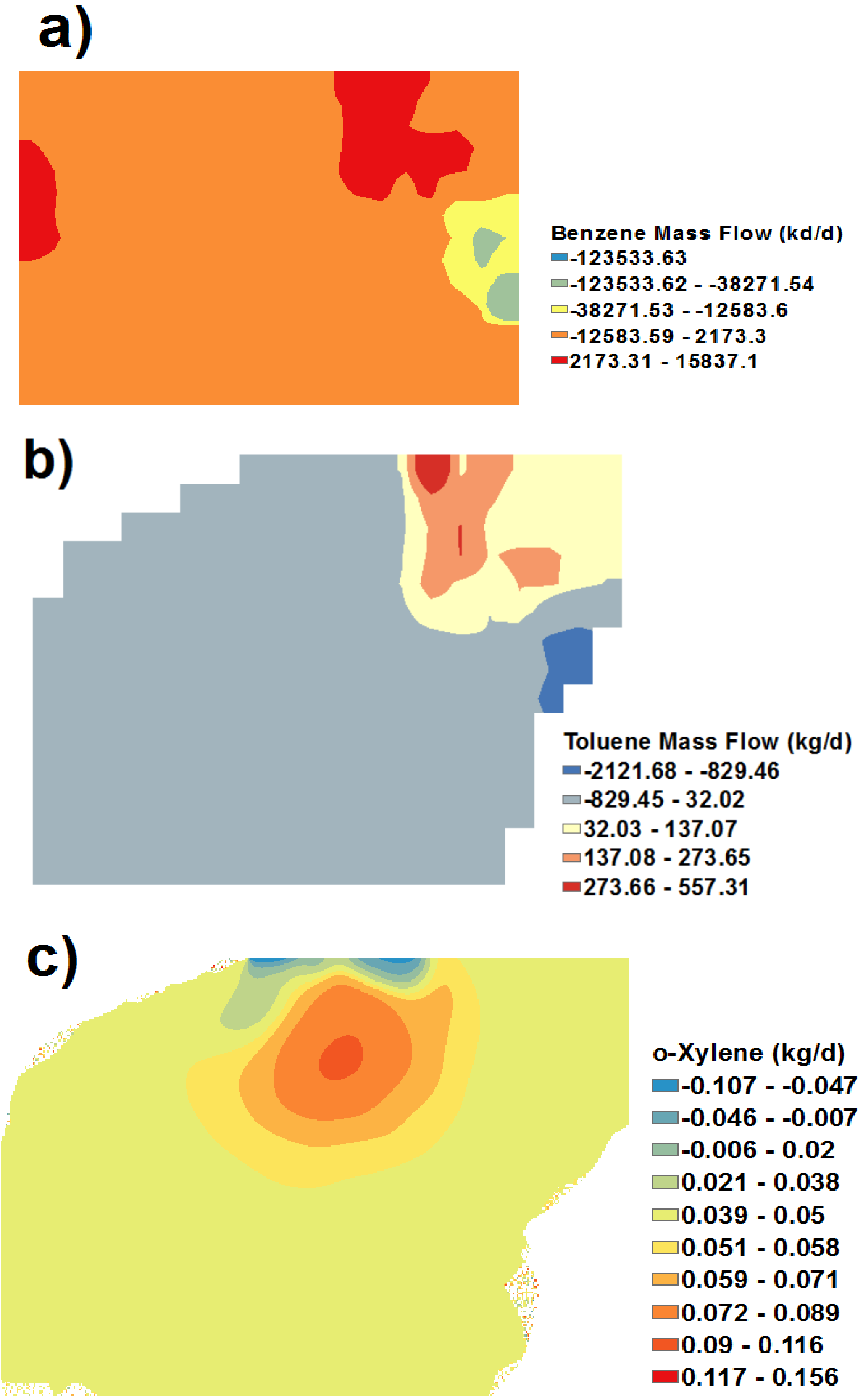


Fig: 12. *Mass Flow in a Carabobo State aquifer, Venezuela: BTEX: a) Benzene, b) Toluene, c) Ethylbenzene*

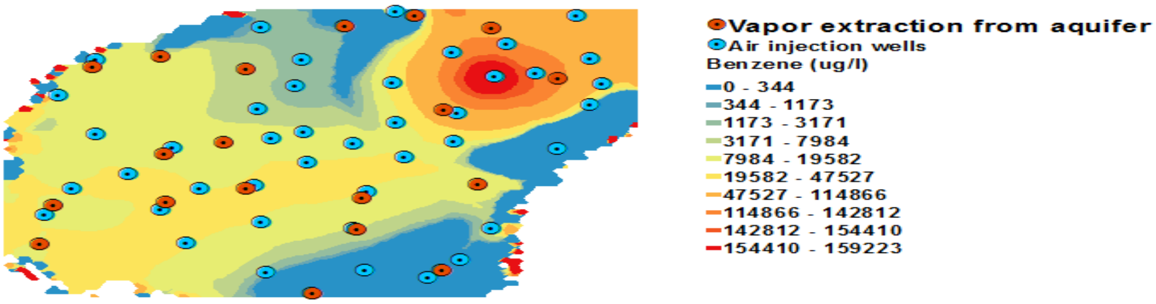


***Fig: 13.** Proposed wells for air injection (42) and vapor extraction (19) in a Carabobo State aquifer polluted with Benzene separated each 100 meters and 150 meters, respectively. The regulatory limit for the Benzene in water is 10 µg/l according to the Sanitary Standard for Drinking Water Quality, Official Gazette Venezuela. Nº 36395 Art. 14.*

***Table: 8.** Statistics for hydraulic parameters in a Carabobo State aquifer, Venezuela: a) Water static level, b) Water dynamic level, c) Hydraulic Gradient, d) Saturated Thickness, e) Flow velocity, f) Flow transmissivity*

Unit N°	**Minimum**	**Maximum**	**Area (m^2)**	**Percentage of area**
Water static level (masl)				
1	407.62	433.00	30596400	55.94
2	433.01	460.81	15021150	27.46
3	460.82	512.64	5155405	9.42
4	512.77	585.51	2149985	3.93
5	585.59	686.10	1767369	3.23
Water dynamic level (masl)				
1	358.09	393.54	27664880	61.36
2	393.54	424.05	11504440	25.51
3	424.06	478.36	1799441	3.99
4	478.44	555.76	2316323	5.13
5	555.86	663.78	1799441	3.99
Hydraulic Gradient (%)				
1	0.01	3.25	37276450	68.17
2	3.25	9.90	12544300	22.94
3	9.91	20.43	2156892	3.94
4	20.45	32.32	1862401	3.41
5	32.33	62.43	844884.2	1.55
Saturated Thickness (m)				
1	35.84277	45.09358	13360000	24.42
2	45.09825	53.95136	21860000	39.96
3	53.96689	66.08061	8322500	15.21
4	66.08842	81.07376	6005000	10.98
5	81.08453	98.28699	5162500	9.44
Flow velocity (m/d)				
1	0.033031	4.699921	37190000	68.75
2	4.706436	13.66623	11750000	21.72
3	13.87682	28.57493	2020000	3.73
4	28.78451	46.18502	1910000	3.53
5	46.61687	84.14056	1220000	2.25
Flow discharge (m^3/d)				
1	330.3056	46999.21	37190000	68.75
2	47064.36	136662.3	11750000	21.72
3	138768.2	285749.3	2020000	3.73
4	287845.1	461850.3	1910000	3.53
5	466168.7	841405.7	1220000	2.25

***Table: 9.** Parameters for remediation using air injection and vapor extraction in a Carabobo State aquifer, Venezuela*

Benzene		
Maximum mass flow of Benzene (Figure 12a)	kg/d	15837
Air density	kg/m^3	1.204
Required air discharge (322.56 cfm)	m^3/d	13153
Molecular weight	g/mol	78.11
Water flow discharge in the aquifer (Figure 11f)	m^3/s	49805
Saturated thickness (Figure 11d)	m	46
Water velocity (L') (Sherwood and Holloway, 1940)	$kg/s\text{-}m^2$	1083
Transfer coefficient of contaminant from water to air, k_La (Sherwood and Holloway, 1940)	$kmol/s.m^3$ $(kmol/m^3)$	0.04
Q(extracted vapor) (125 cfm)	m^3/d	5075
Toluene		
Maximum mass flow of Toluene (Figure 12b)	kg/d	557.31
Air density	kg/m^3	1.204
Required air discharge (11.35 CFM)	m^3/d	462.88
Molecular weight	g/mol	92.13
Water flow discharge in the aquifer (Figure 11f)	m^3/s	49805
Saturated thickness (Figure 11d)	m	46
Water velocity (L') (Sherwood and Holloway, 1940)	$kg/s\text{-}m^2$	1083
Absorption coefficient of oxygen in water k_La (Sherwood and Holloway, 1940)	$kmol/s.m^3$ $(kmol/m^3)$	0.04
Q(extracted vapor) (3.7 cfm)	m^3/d	6.28
o-Xylene		
Maximum mass flow of Toluene (Figure 12c)	kg/d	0.156
Air density	kg/m^3	1.204
Required air discharge (0.0137 cfm)	m^3/d	0.129
Molecular weight	g/mol	106.16
Water flow discharge in the aquifer (Figure 11f)	m^3/s	49805
Saturated thickness (Figure 11d)	m	46
Water velocity (L') (Sherwood and Holloway, 1940)	$kg/s\text{-}m^2$	1083
Absorption coefficient of oxygen in water k_La (Sherwood and Holloway, 1940)	$kmol/s.m^3$ $(kmol/m^3)$	0.04
Q(extracted vapor) (0.000882 cfm)	m^3/d	0.036

DISCUSSION OF RESULTS

The analysis of physical characteristics indicates that the contamination with hydrocarbons is occurring in the northern region of the La Guacamaya aquifer implying that the contaminants might be transported toward downstream of the aquifer causing a potential great impact on the water for human consumption and industrial uses. The condition of the confined aquifer due to the alternating layers of low plasticity clay with well graded sand has avoided that the hydrocarbons in the soil reach upper values to the environmental regulation. In case of hydrocarbon tests in soils, the TPH-GRO (C_6-C_{10}) measured in PM-5 in a maximum magnitude is of 142 mg/kg of soil for a depth varying between 6 and 6.5 m, it has been found below to the generic limits based on the risk dictated by the Environmental Ministry (2006) in Colombia; which is 1000 mg/kg. In the case of Lead measured in PM-4 in a maximum magnitude of 129 mg/kg of soil for a depth varying between 1.5 and 2.0 m, it has been found below to the generic limits based on the risk dictated by EPA, (1997); which is 530 mg/kg.

In the case of BTEX, Benzene measured in PM-6 has a maximum magnitude of 1.234 mg/kg of soil for a depth varying between 4.5 and 5.0 m, it has been found below to the generic limits based on the risk dictated by Ministry of Space Planning and Environment, Department of Soil Protection, Dutch Standard (2014); which is 2 mg/kg. In the case of Toluene measured in PM-6 in a maximum magnitude of 2.072 mg/kg of soil for a depth varying between 4.5 and 5.0 m, it has been found below to the generic limits based on the risk dictated by Ministry of Space Planning and Environment, Department of Soil Protection, Dutch Standard (2014); which is 50 mg/kg. In the case of Ethylbenzene measured in PM-5 in a maximum magnitude of 1.097 mg/kg of soil for a depth varying between 6.0 and 6.5 m, it has been found below to the generic limits based on the risk dictated by Ministry of Space Planning and Environment, Department of Soil Protection, Dutch Standard (2014); which is 130 mg/kg. In the case of m.Xylene measured in PM-5 in a maximum magnitude of 2.614 mg/kg of soil for a depth varying between 6.0 and 6.5 m, it has been found below to the generic limits based on the risk dictated by Ministry of Space Planning and Environment, Department of Soil Protection, Dutch Standard (2014); which is 50 mg/kg. In the case of o.Xylene measured in PM-5 in a maximum magnitude of 0.978 mg/kg of soil for a depth varying between 6.0 and 6.5 m, it has been found below to the generic limits based on the risk dictated by Ministry of Space Planning and Environment, Department of Soil Protection, Dutch Standard (2014); which is 50 mg/kg. In the case of MTBE measured in PM-6 and PM-12 in a maximum magnitude of 3.281 mg/kg of soil for a depth varying between 4.5 and 5 m, it has been found below to the generic limits based on the risk dictated by EPA (2009); which is 39 mg/kg.

In case of hydrocarbon tests in water, the TPH measured in PM-2 (0.8 mg/l), PM-3 (0.4 mg/l), PM-4 (0.9 mg/l), PM-6 (2.3 mg/l), PM-8 (0.4 mg/l), PM-9 (0.7 mg/l), PM-10 (0.4 mg/l), PM-13 (0.6 mg/l), PM-15 (0.5 mg/l), it has been found upper to the generic limits based on the risk dictated by the Ministry of the Environment, Housing and Sustainable Development. Colombia (in drinking water); which is 0.32 mg/l. In case of hydrocarbon tests in water, the TPH-GRO measured in PM-1 (275.4 mg/l), PM-5 (76.4 mg/l), PM-6 (210.2 mg/l), PM-9 (19.006 mg/l), PM-10 (679.14 mg/l), PM-11 (275.39 mg/l), PM-14 (6.92 mg/l), it has been found upper to the generic limits based on the risk dictated by the Environmental Ministry (2006) in Colombia; which is 4 mg/l. In the case of Lead measured in PM-1 to PM-15 in a maximum magnitude of 0.01 mg/l of water, it has been found upper to the generic limits based on the risk dictated by Ministry of Space Planning and Environment, Department of Soil Protection, Dutch Standard (2014); which is 75 mg/l.

In the case of BTEX measured in water, Benzene measured in PM-1 (23945 µg/l), PM-5 (8.2 µg/l), PM-6 (13000 µg/l), PM-9 (4582 µg/l), PM-10 (36760 ug/l), PM-11 (30270 µg/l), it has been found upper to the generic limits based on the risk dictated by the Sanitary Standard for Drinking Water Quality, Official Gazette Venezuela. Nº 36395 Art. 14, which is 10 µg/l. In the case of Toluene measured in PM-1 (19715 µg/l), PM-5 (1180 µg/l), PM-9 (784 µg/l), PM-10 (44850 µg/l), PM-11 (38900 µg/l), it has been found upper to the generic limits based on the risk dictated by the Sanitary Standard for Drinking Water Quality, Official Gazette Venezuela. Nº 36395 Art. 14, which is 700 µg/l. In the case of Ethylbenzene measured in PM-1 (2145 µg/l), PM-5 (1340 µg/l), PM-9 (518 µg/l), PM-10 (1690 µg/l), PM-11 (5130 µg/l), it has been found upper to the generic limits based on the risk dictated by the Sanitary Standard for Drinking Water Quality, Official Gazette Venezuela. Nº 36395 Art. 14, which is 300 µg/l. In the case of m.Xylene measured in PM-1 (14065 µg/l), PM-5 (6120 µg/l), PM-9 (5998 µg/l), PM-10 (1123 µg/l), PM-11 (1123 µg/l), it has been found upper to the generic limits based on the risk dictated by the Sanitary Standard for Drinking Water Quality, Official Gazette Venezuela. Nº 36395 Art. 14, which is 500 µg/l. In the case of o.Xylene measured in PM-1 (3965 µg/l), PM-9 (824 µg/l), PM-10 (4580 µg/l), PM-11 (4830 µg/l), it has been found upper to the generic limits based on the risk dictated by the Sanitary Standard for Drinking Water Quality, Official Gazette Venezuela. Nº 36395 Art. 14, which is 500 µg/l. In the case of MTBE measured in PM-1 (208600 µg/l), PM-5 (58920 µg/l), PM-6 (177180 µg/l), PM-9 (5522 µg/l), PM-10 (570593µg/l), PM-11 (115380 µg/l), PM-12 (21 µg/l), PM-14 (5430 µg/l), it has been found upper to the generic limits based on the risk dictated by EPA (1997), which is 20 µg/l.

The spatial prediction models indicate to the PM-4 and PM-12 as the source of contamination of soil by TPH and congeners and Lead. In all cases, the spatial prediction is explained by a local polynomial interpolation with order 3. The gradient of linear regression function varies between 0.28 and 0.94. The spatial prediction models indicate to the PM-6, PM-13 and PM-15 as the source of contamination of soil by BTEX and MTBE. In all cases, the spatial prediction is explained by a local polynomial interpolation with order 3. The gradient of linear regression function varies between 0.34 and 0.94.

The spatial prediction models indicate to the PM-6, PM-7 and PM-15 as the source of contamination of water by TPH and congeners and Lead. In all cases, the spatial prediction is explained by a local polynomial interpolation with orders 2 and 3. The gradient of linear regression function varies between 0.27 and 0.57. The spatial prediction models indicate to the PM-6, PM-13 and PM-15 as the source of contamination of water by BTEX and MTBE. In all cases, the spatial prediction is explained by a local polynomial interpolation with orders 2 and 3. The gradient of linear regression function varies between 0.41 and 1.44.

With respect to the proposal of remediation applying air injection and vapor extraction, the benzene is the component, which requires the greatest demand of air and generates the greatest amount of vapor by comparing to the estimations of these parameters for the Toluene and o-Xylene in water. For the Benzene, the required air is 13153 m^3/d (323 cfm) and the vapor extraction is 5075 m^3/d (125 cfm).

CONCLUSIONS

The contamination with hydrocarbons is occurring in the northern region of an aquifer of the Carabobo State implying that the contaminants might be transported toward downstream of the aquifer causing a potential great impact on the water for human consumption and industrial uses. The condition of the confined aquifer due to the alternating layers of low plasticity clay with well graded sand has avoided that the hydrocarbons in the soil reach upper values to the environmental regulation. In the case of water, the contamination with hydrocarborns is upper to the environmental regulation.

In general, in both soil and water, the spatial prediction of hydrocarbons is explained by a local polynomial interpolation whose order varies between 2 and 3, and in a smaller proportion by the global interpolation whose order varying between 2 and 3. The Kernell functions used are Exponential, Gaussian, Epanechnikov and Quartic. The gradient of linear regression function varies between 0.34 and 0.94, resulting in a moderate to excellent adjustment.

The proposal of remediation consists of applying air injection and vapor extraction, being the required air of 13153 m^3/d (323 cfm) and the vapor extraction of 5075 m^3/d (125 cfm).

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Cite this article as:
Dr. Adriana Márquez Romance, Dr. Edilberto Guevara Pérez, & Dr. Demetrio Rey Lago. (2018). Soil and Groundwater Remediation Proposal in an Aquifer of Venezuela by Hydrocarbon Transport Geostatistical Modeling. Journal of Remote Sensing GIS & Technology, 5(1), 15–43. http://doi.org/10.5281/zenodo.1492031